A Computational Approach to Aircraft Engine Noise Propagation and Scattering

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Field Method Approaches

- Time-domain Linear/Nonlinear Model
  - Advantages: all frequencies up to the limit of the resolution can be modeled together in a single run; requires smaller amount of computer memory.
  - Disadvantages: possibly larger wall-clock time for one run; stability for viscous mean flow unclear.
- Frequency-domain Linear Model
  - Advantages: can produce faster results for a single frequency.
  - Disadvantages: needs large amounts of computer memory to store and solve the complex linear algebra problem.

Time-domain Nonlinear Model

- The nonlinear inviscid flow (Euler) equations

$$\frac{\partial Q}{\partial t} + \sum_{d=1}^{3} \frac{\partial F_d}{\partial x_d} = 0$$

$$Q = \begin{pmatrix} \rho \\ \rho v_1 \\ \rho v_2 \\ \rho v_3 \\ \rho E \end{pmatrix}, \; F_d = \begin{pmatrix} \rho v_d \\ \rho v_1 v_d + p\delta_{1d} \\ \rho v_2 v_d + p\delta_{2d} \\ \rho v_3 v_d + p\delta_{3d} \\ (\rho E + p) v_d \end{pmatrix}$$

are considered to govern noise propagation.

- Solution Q is searched in a trial space of orthogonal three-dimensional polynomials (spectral approximation)

$$Q(t,x,y,z)=\sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{N}Q_{ijk}(t)h_i(x)h_j(y)h_k(z)$$

- After a Galerkin projection, the governing equations are reduced to

$$\frac{dQ_{ijk}}{dt}=-\left[D^x+D^y+D^z\right]\mathbf{F}$$

  where the right-hand side is a sum of discrete differential operators evaluated numerically.

- These equations represent a system of ODEs for Q_{ijk} that is integrated in time using a $2N$-storage wave-optimized Runge-Kutta method.

Acoustic computations strategy

- First the (inviscid) mean flow is computed using the same method/grid subject to steady-state boundary conditions, and stored in memory.
- The total flow field variables are then computed using time-dependent boundary conditions that specify the incoming modes; acoustic variables can be obtained by subtracting the mean flow.
- For a viscous mean flow $\mathbf{F_0}$ (obtained by other solvers, not a solution to the governing equations), the same nonlinear model can be used by subtracting $[D^x + D^y + D^z]\,\mathbf{F_0}$ from the RHS of the equations. **Stability is being investigated.**

Parallelization strategy

- The DG method is highly parallelizable using the message-passing strategy: information between neighboring elements needs to be known only on element faces (lower dimensional manifold.)
- Overlapping of communication and computation is possible by first computing and communicating fluxes in elements near the partition boundaries. The other elements computed while communication proceeds.
- Good speed-ups have been obtained even on small grids (884 elements on 16 processors; grid decomposed using the multilevel strategy in METIS).

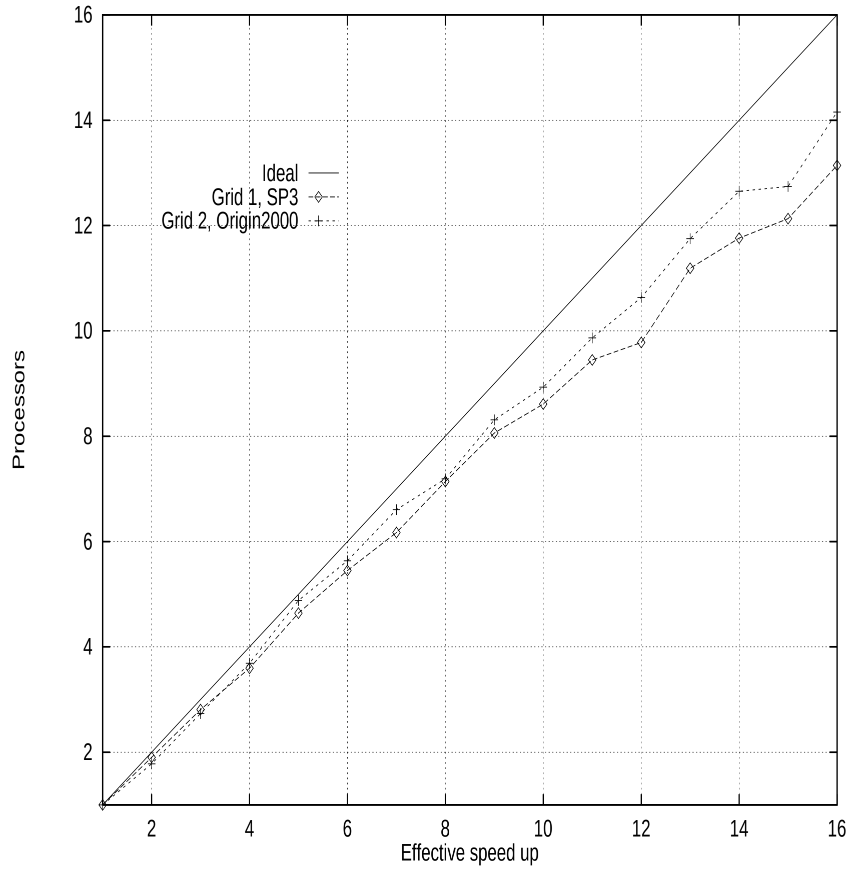

Figure 1: Parallel performance for two test cases. Grid 1: 884 elements. Grid 2: 17,370 elements. "Bad" performance (grid 2 on 15 processors) due to "bad" domain decomposition (many cut faces).

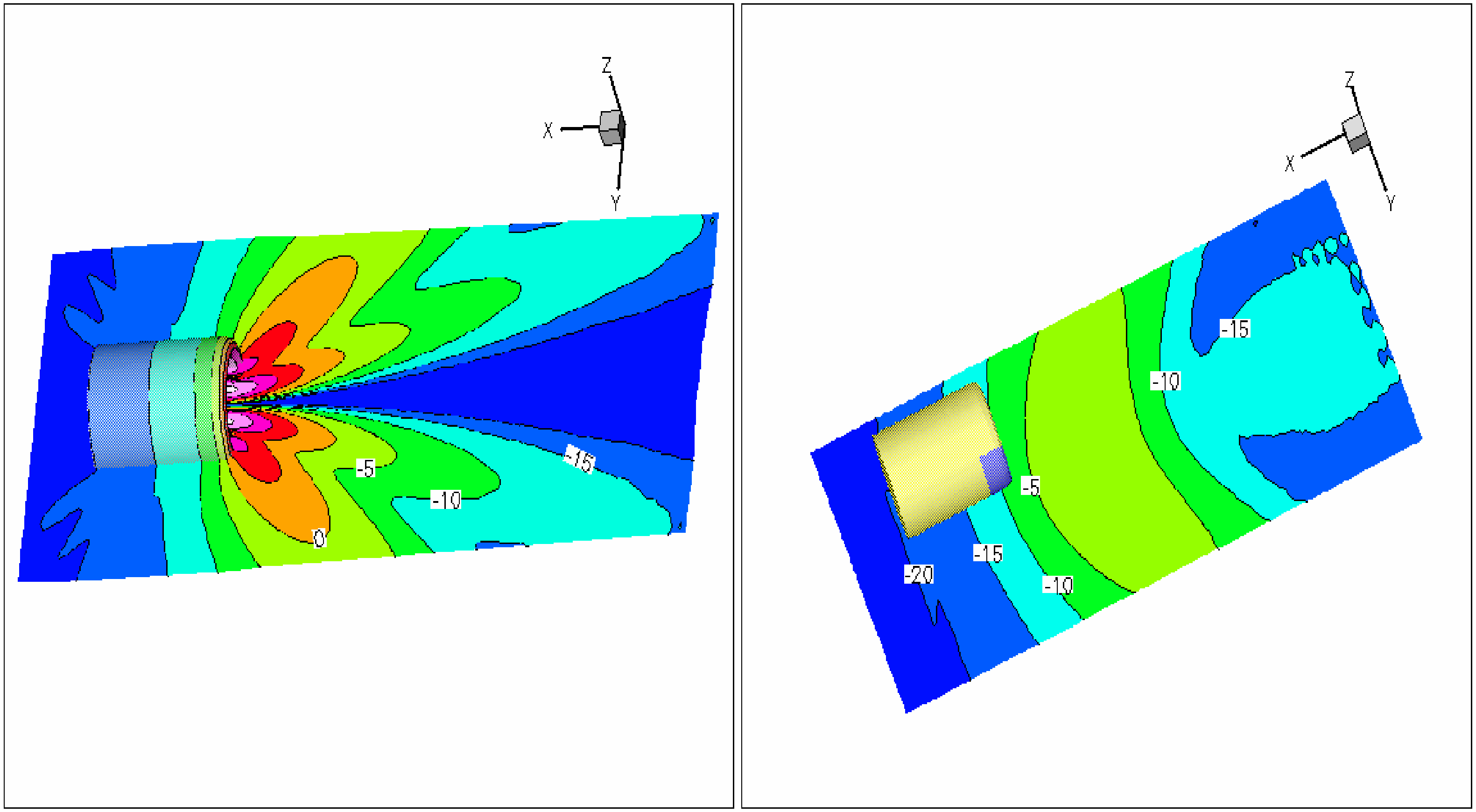

Figure 2: SPL contours for radiation of spinning mode $(2, 1)$ from an axisymmetric bell-mouth nacelle at reduced frequency $\omega = 8.0$ and $M_\infty = 0$. Nacelle surface and plane through its axis (left); plane $z = -4$ (right). $3, 402, 217$ discretization points.

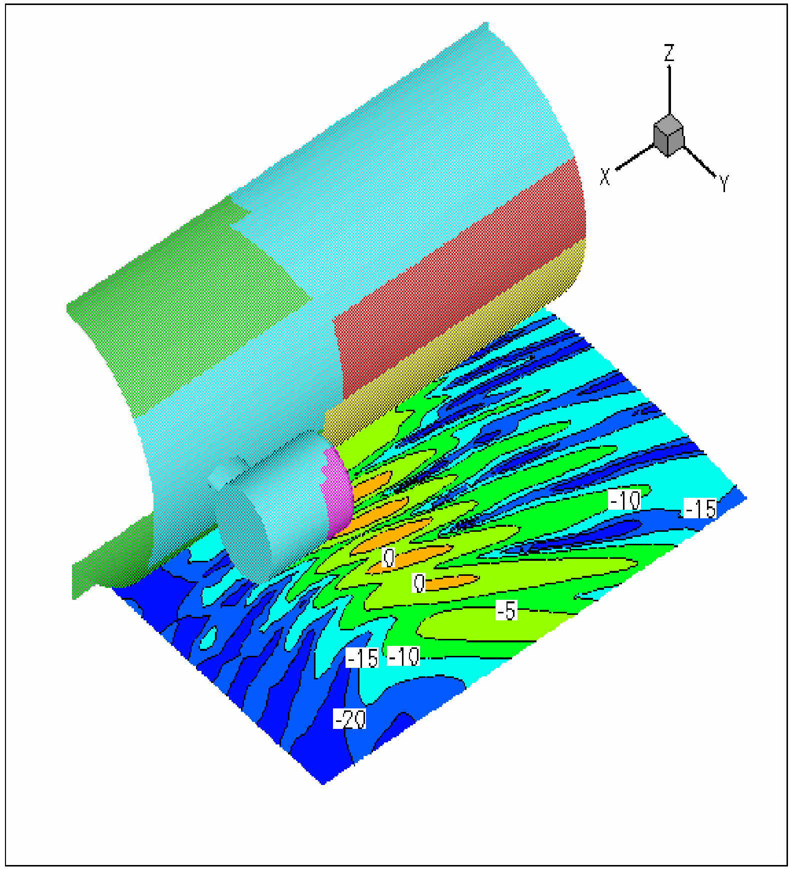

Figure 3: SPL contours for the same case when the nacelle is mounted on a fuselage, plane $z = -4$. Trace of mesh decomposition shown on the solid surfaces. $5,957,910$ discretization points.

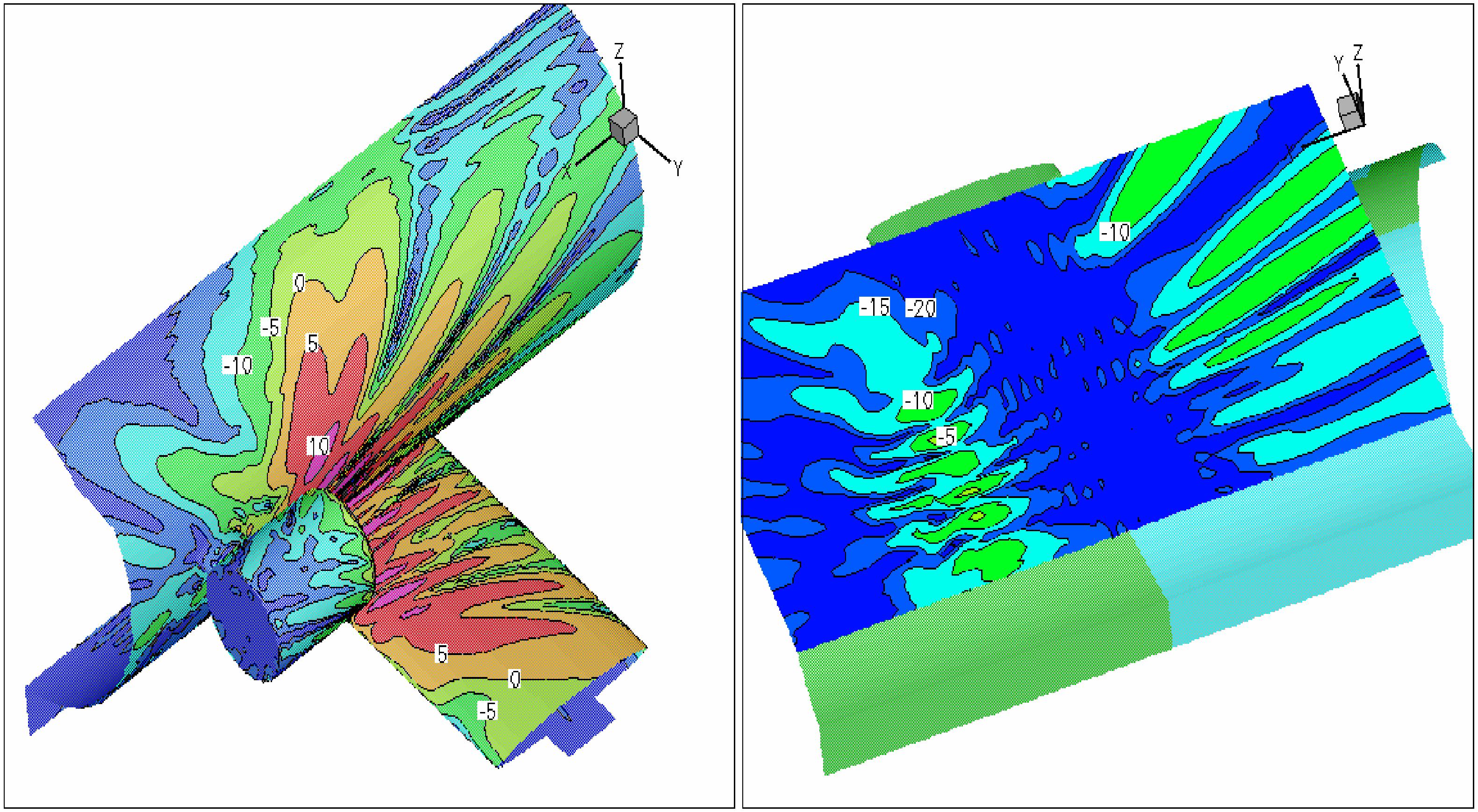

Figure 4: SPL contours for the same case when a wing is added to the configuration. Solid surfaces (left); plane $z = -4$ seen from below (right). $7,835,149$ discretization points.

Conclusions and Future Development

- Largest run to date: 7,835,149 points, 39,000,000 DOFs, 1.5GB storage (reduced frequency ω=8.0); 250 hrs. run on 16 processors, IBM SP3 at 375MHz.
- For industrial use at around ω=20.0, must fine-tune the code for improved performance.
- Current radiation boundary conditions (damping layer type) do not always perform well at domain corners (i.e. Fig. 4 left, upper-right corner).
- Multiple sources (engines), improved radiation boundary conditions and viscous flow capability to be added.